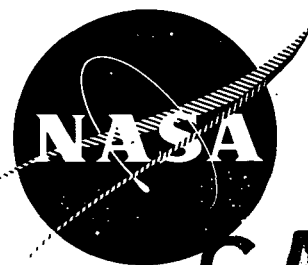


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FIRE EXTINGUISHMENT IN OXYGEN ENRICHED ATMOSPHERES

by A. F. Robertson and M. W. Rappaport

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16. Abstract Current state-of-the-art of fire suppression and extinguishment techniques in oxygen enriched atmosphere is reviewed. Four classes of extinguishment action are considered: cooling, separation of reactants, dilution or removal of fuel, and use of chemically reactive agents. Current practice seems to show preference for very fast acting water spray applications to all interior surfaces of earth-based chambers. In space, reliance has been placed on fire prevention methods through the removal of ignition sources and use of nonflammable materials. Recommendations are made for further work related to fire suppression and extinguishment in oxygen enriched atmospheres, and an extensive bibliography is appended.			
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FIRE EXTINGUISHMENT IN OXYGEN ENRICHED ATMOSPHERES

A. F. Robertson and Miriam W. Rappaport

SUMMARY

Ignition, flammability, and fire spread in oxygen enriched atmospheres are briefly reviewed; and attention is directed to fire suppression and extinguishment in hypobaric and hyperbaric chambers at normal, reduced, and zero gravity. Four classes of fire extinguishment are considered: cooling, separation of reactants, dilution or removal of fuel, and use of chemically reactive agents. The current position relating to fire suppression in oxygen enriched atmospheres is reviewed.

For earth-based systems, water has been preferred over other extinguishing agents. Experience shows that because of the high flammability of many materials, fire suppression action must be activated coincident with or immediately after ignition. Several fatalities have occurred within 15 seconds after ignition. As a result, there appears to be a strong preference for automatically activated fire suppression equipment. If activation devices can be selected to discriminate and report fires of smoldering character, the use of hand-held hoses may serve to minimize the inconvenience of general spray application which may present a special problem in the case of false alarms.

In space, the weight penalty, cleanup problems, and hazards to electronic equipment have apparently limited adoption of water spray extinguishing systems. While a hand-held foam generation extinguisher has been developed for use on small fires that might occur in the Apollo spacecraft, prime emphasis seems to have been directed toward development and use of materials with very low ignition and flammable hazard characteristics. Both inert and chemically reactive compounds such as the halons have been considered, but to date these do not appear to have been widely accepted for use in compartments inhabited by humans.

Recommendations for further work are offered which relate to more efficient use of water, better design procedures for spray systems, localized reactive water spray systems, further study of CF_4 as an inerting agent, aseptic foam systems for medical use, experiments for study of fires under zero gravity conditions in the presence of gas convection, and improved materials of low ignition and flammable hazard characteristics.

A bibliography of over 150 references is included.

Fire Extinguishment in Oxygen Enriched Atmospheres

by

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1. Introduction

There has long been recognition of the fire hazards involved with ignition of fuels in oxygen enriched atmospheres.* The flash fire resulting from the insertion of a glowing wood splint into a test tube of oxygen has been a common chemical laboratory demonstration. Accidents following the introduction of compressed oxygen cylinders about 80 years ago drew attention to the associated fire and explosion hazards present when organic materials are exposed to the compressed gas. Furthermore, liquid oxygen saturated cellulosic materials have been used as explosives. Such materials exhibit the unique feature of losing shock sensitivity and explosive characteristics when they are warmed, thereby permitting evaporation and dispersal of their oxygen.

The problem of increased flammability under oxygen enriched atmospheres was recognized and discussed in the 1934 edition of the NFPA standard entitled, "Anesthetic Gases and Oxygen in Hospitals." More recently, prompted by the increased use of oxygen enriched atmospheres in medical, space, and underwater activities, NFPA published its manual, "Fire Hazards in Oxygen Enriched Atmospheres" (1). Hypobaric and hyperbaric standards are defined in two other NFPA publications (2) (3).

*For the purpose of this paper, an oxygen enriched atmosphere is defined as one in which the oxygen content exceeds 21 percent by volume or the partial pressure of oxygen exceeds 160 millimeters of mercury.

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Thus, when plans were being developed for both manned space vehicles and undersea chambers with enriched or even pure oxygen atmospheres, considerable attention was given to the safety problem. Attempts were made to design for safety in spite of the imposed danger. The surveys by Cicotti (4) and Roth (5) were especially comprehensive and of great merit. Many others (6) (7) (8) (9) (10) contributed to analysis of the problem. However, in spite of recognition of the hazards and attempts to plan for the safety of mission assignments, accidents have occurred. Eleven such accidents in hyperbaric and hypobaric chambers, during the period 1945-1971, were analyzed by Alger and Nichols (11). Table I, reproduced from their paper, provides a useful way of characterizing the problem, at least so far as these incidents may be considered typical. The Apollo fire was one of those analyzed in their paper. It has been the subject of extensive study (12).

In ten of the incidents discussed by Alger and Nichols, the suspected ignition source was electrical wiring. In six of these, the electrical insulation material was believed to have served as the primary fuel; and in nine instances, the secondary fuel was cellulosic or plastic materials. In five of the incidents, the fire exposure prior to fatality was less than 90 seconds; and in three incidents, exposure periods of less than 15 seconds resulted in fatalities. In summary, electrical faults were the most prevalent ignition source and, in most instances, electrical insulation served as the primary material ignited. The rapid fire growth after ignition under these conditions leaves little time for fire suppression measures prior to attainment of lethal conditions.

This present paper reviews the state-of-the-art of fire extinguishment under hypobaric and hyperbaric oxygen enriched conditions. Limited data on fire behavior under zero gravity conditions are at hand. Those available form the basis of consideration given to modified extinguishment problems posed through absence of acceleration or gravitational forces. Before discussion of fire extinguishment, however, it seems desirable to make reference to some fire and combustion phenomena which are likely to relate to the extinguishment problem.

2. Ignition and Combustion

The ability to control and use fire for his benefit has been a characteristic which is unique to man. In his study of fires for useful ends, he has referred to his work as "combustion research." On the other hand, the study of unwanted or accidental fires has usually been referred to as "fire research." The former is directed toward deriving benefits from fires and usually involves studies of the burning characteristics of purposely mixed fuels and oxidizers. Fire research and protection studies involve investigation of the unwanted fire and means for its prevention, control, and extinguishment. These fires

usually involve diffusion flames or flames in which the reaction occurs at an interface, often very poorly defined, between the pyrolysis products of a fuel, usually in gaseous form, and air or some other oxidizer, again usually in gaseous form. The two reacting materials diffuse or are otherwise mixed together to form a reaction zone where burning occurs. The unwanted fire can be further differentiated from most desirable fires by its transient nature. It is either growing or diminishing in size and its nature is continually changing.

While there are exceptions, fires usually involve combustion of fuel in a gaseous form. Thus, it is not the wax that is burning in a candle diffusion flame, but the vapors which are volatilized from the molten wax that rises through the wick and approaches the base of the flame. In a similar way, close inspection of a splint or match as it burns shows that as the flame travels along the stick, a blue, almost transparent, flame seems to surround the solid stick without really touching it. The wood is being heated by radiation and gaseous conduction, and volatile gases are distilled and pyrolyzed from the solid. It is the gas that burns rather than the solid material.

The ignition process thus involves a localized supply of heat to the fuel sufficient to pyrolyze or volatilize a portion of it in the presence of an oxidizer. In addition, there must be heating of the gaseous mixture to a temperature sufficiently high that the fuel-oxidizer reaction results in heating at a rate greater than that of the thermal loss to the solid source of the fuel and to the surroundings. Whether this ignition incident develops into a spreading fire will depend on a variety of factors, including the important feedback of heat from the initial fuel ignition to the solid from which the flammable gases are generated, the quantity and geometry of the fuel arrangement, and the continued supply of an oxidizer to the vicinity of the hot fuel gases.

2.1 Factors Influencing Flame Spread Rate

Combustion research workers have made great strides in the last 30 years in their attempts to understand and predict the burning behavior of fuels under controlled conditions. However, attempts by the fire research community to define the characteristics of unwanted fires have not made similar progress. The reason for this is the transient nature and the great number of physical and chemical variables which influence the growth and spread of such fires. A simple and interesting picture of some of the complexities of just one aspect of a fire, its spread across the surface of a material, is presented by Friedman (13). In "A Survey of Knowledge About Idealized Fire Spread Over Surfaces," he makes use of simple burning experiments to show the following points:

- a. As the roughness or surface-to-volume ratio of a fuel increases, the flame spread rate over its surface may increase by several orders of magnitude.
- b. Fire spread rate over a horizontal fuel bed increases exponentially with the air velocity.
- c. Flame spread rate over a cellulosic fuel is inversely related to the moisture content of the fuel.
- d. A uniform speed creeping mode of horizontal, downward, and even moderately inclined upward flame spread exists for some materials. The vertical upward flame spread rate may be unstable, but is roughly an order of magnitude faster than for the creeping mode.
- e. Increase of pressure of normal air by a factor of ten may increase the creeping flame spread rate by a factor of two. If the atmosphere involved is highly oxygen enriched, the flame spread increase may approach direct relationship to the pressure increase.
- f. Flame spread rate, under otherwise constant conditions, may vary by at least one order of magnitude depending on material composition.
- g. Flame spread rate may vary several-fold as a result of changes in lateral dimensions of the burning object.
- h. At constant pressure and varying oxygen concentration, the flame spread rate may vary as a power function of oxygen concentration, the exponent varying from one to three depending on material properties.
- i. Although some exceptions exist data suggest that direct substitution of helium for nitrogen in an oxygen-nitrogen atmosphere results in increased flame spread rate.

It is no wonder that attempts to develop a mathematical model of flame spread behavior have proved difficult. Nevertheless, some success has been achieved in this field by de Ris and Parker who have independently developed relationships characterizing downward fire spread across

a thin fuel bed (15) (16). Both of these apply to laminar diffusion burning across a thin solid fuel surface and yield similar relationships

$$v = \frac{\lambda \sqrt{2}}{\rho c \tau} \frac{(T_{\text{flame}} - T_{\text{vap}})}{(T_{\text{vap}} - T_{\infty})}$$

where:

- v = flame progression rate over fuel
- λ = thermal conductivity of gas at the fuel surface
- τ = the half thickness of the thin fuel bed
- ρ = the density of the fuel bed material
- c = the specific heat of the fuel bed material
- $T_{\text{flame}} - T_{\text{vap}}$ = flame gas temperature excess above fuel vaporization or pyrolysis temperature
- $T_{\text{vap}} - T_{\infty}$ = fuel vaporization or pyrolysis temperature excess above ambient

The de Ris work is more comprehensive since it extends to the case of thermally thick fuel beds. Further, de Ris was able to correlate the excellent experimental data developed by Lastrina et al (14) for downward burning of 0.009 and 0.08 in.* thick cellulosic sheets in oxygen-nitrogen atmospheres of varying compositions as well as pure oxygen, and in pressure from about 0.41 to 22 atmospheres. On the basis of this correlation, de Ris questions the gas phase reaction kinetics as an important rate controlling factor in the region and burning type explored. However, for lower oxygen concentration in the ambient he concedes that gas phase inhibitors may have increasing effectiveness. The original plot by Lastrina and the correlation by de Ris are reproduced in Figures 1 and 2 (14). In Figure 2, the ordinate may be assumed proportional to the flame spread rate, while the abscissa is proportional to pressure. Considering the number and range of variables involved, the correlation achieved suggests real progress.

While the data discussed here relate only to downward burning of cellulosic fuels, it would be expected that similar methods would be successful in defining the behavior of other fuel types as long as the assumptions involved in the analysis apply.

* The units reported in the text are those used in the references cited. A table for conversion to SI units is provided on page 24.

2.2 Fires in Hypobaric and Hyperbaric Atmospheres

Some aspects of the flammability problem pertinent to the subject of this paper are reviewed to illustrate reasons for the complexity of the extinguishment problem in enclosed environments.

Increased oxygen in the atmosphere reduces the number of materials which may be considered noncombustible and increases ignition probability, flame spread rate, and the rate of release of energy. In space these conditions present a real problem since evacuation and other more normal reactions to fire are not likely to be available. Even with adequate onboard fire fighting equipment, as Huggett (7) states, "not only must the occupants be able to survive for a time after the fire is extinguished, but the system must retain a degree of operability that will permit a return to a more friendly external environment where evacuation will be possible." In another reference, Huggett (17) comments on the toxic hazards likely to be encountered. "Spacecraft fires will have a limited oxygen supply, the products of combustion will not differ qualitatively in composition or toxicity from those obtained by burning of the same materials in a limited supply of air."

Many research groups have shown that flammability, in general, increases with oxygen concentration at fixed total pressure, and less rapidly with pressure at fixed volumetric concentration of oxygen (7) (9) (10) and (18). Figure 3 from Dorr (10) presents data on the flame spread rate of filter paper strips burned at an angle of 45° under a range of atmospheric compositions and pressures. Kuchta (18) and Fisher (19) have shown that the hot plate self-ignition temperature of materials is not very sensitive to, but decreases slowly with, increase of oxygen partial pressure, Figure 4. On the other hand, electric spark energy required for ignition appears to be inversely related to oxygen partial pressure (20). Huggett (7) and (17) suggests that flammability of a given material is inversely related to the heat capacity of the ambient gas mixture.

Huggett (17) reports that slightly more energy is required to ignite materials in oxygen-helium atmospheres than in oxygen-nitrogen, but the effect is so slight that there is little if any reduction in fire hazard. This is of special note since the flame spreads more rapidly in the oxygen-helium atmosphere. The reduction of ignition sensitivity with oxygen-helium mixtures is attributed more to a rapid dissipation of energy, which delays attainment of critical temperature, rather than to differences in the ignition process itself. On the other hand, flame spread rates are reported as being largely influenced by flame temperatures (17). One of the most recent and comprehensive surveys of the flammability question is presented by McGee (21).

Denison (22) and (23) reports a relevant series of experiments in which he determined the total ambient pressures of pure or diluted oxygen under which manual responses would be inadequate to prevent (a) ignition of overalls and (b) production of 50% skin burn area after ignition of covering overalls. The data reported were at the observed oxygen partial pressure necessary to result in the two types of damage within times of less than 5 seconds and less than 20 seconds. These two time intervals were selected as representative of the range likely to be achieved in human manual response to an ignition incident. In these experiments, both new and worn, dry and nondry overalls were purposely used and skin burn injury was assessed with the use of clothed dead pigs. The data are reproduced in Table II. It is evident that quick response is necessary if serious skin burns are to be prevented under the conditions simulated by this study.

2.3 Zero Gravity Conditions

So far our brief review of ignition and combustion phenomena has been confined to conditions under the influence of the earth's gravitational field. In space, zero or very low gravitational fields can exist for most of the active mission duration. The creation of a zero gravitational field on the earth for study of combustion phenomena has been limited to drop tests in which an experimental enclosure is allowed to fall freely, or to aircraft flights in special parabolic courses. In the former, the useful experiment periods achieved have been limited to about 5 seconds*, while periods of weightlessness up to about 28 seconds have been achieved in the latter. Kumagai (24), Kimzey (25), Cochran (26), and Abduragimov (27) have conducted fire experiments on burning fuel oil drops, Teflon insulated wire, and gas diffusion flames during drop tests. Hall (28), Kimzey (29), and Neustein (30) have conducted experiments with aircraft flights. The materials studied included candle flames and a wide variety of polymeric materials and fabric strips. Neustein's experiments (30), apparently the most comprehensive, included studies of flame spread along fabric strips under conditions of zero to 5 times gravitational acceleration. Fire behavior was studied in pure oxygen, oxygen-helium, oxygen-neon, and oxygen-nitrogen mixtures at pressures varying from 3.5 to 14.7 psia. The mixed gas systems all involved a partial pressure of oxygen of 3.5 psia. It was observed that ignition was not noticeably influenced in the range of acceleration explored, but that burning rate was significantly dependent on acceleration as a result of modified convection. Figure 5, reproduced from the Neustein report, presents a small portion of the data.

* The authors are informed that the zero gravity facility at the NASA Lewis Laboratory can provide a weightless condition for 10 seconds maximum.

In general, there seems to be agreement that under zero gravity conditions the absence of buoyancy effects will tend to delay dispersal of combustion products from the fire zone and, in many cases, the fires will stifle in their combustion products and become extinguished. Most of the experiments have been performed under still air conditions. Neustein (30) mentions a very rapid flash combustion of the sample and unmixed fuel gases on the loss of zero gravity conditions. Presumably the normal air movement required for atmospheric processing in a space cabin could provide adequate convection over the sample to permit more active burning under conditions of zero gravity.

2.4 Summary

In summary, it is clear that the oxygen enriched atmosphere in hypobaric and hyperbaric chambers can mildly increase the sensitivity of materials to hot plate ignition, significantly increase spark ignition sensitivity, and drastically increase the burning rate of materials. If ignitable materials are present in any significant quantities, provisions must be made first to prevent their exposure to an ignition source; and second, in the event of an ignition, to provide very prompt application of a fire extinguishing agent. The limited information on fire behavior under zero gravity conditions suggests that, without forced convection, the absence of thermal buoyancy forces greatly retards fire growth and spread.

3. Extinguishment

The NFPA Handbook of Fire Protection (31) identifies four ways in which extinguishing agents may be effective in suppressing a fire: (a) cooling, (b) separation of reactants, (c) dilution or removal of the fuel, and (d) chemical action. Any one or a combination of these may provide the means through which a particular agent acts. Further, classes A, B, C, and D are used to designate cellulosic or polymeric, flammable liquid, electrical, and magnesium or other flammable metal-type fires, respectively. It is assumed that most fires of concern in chambers will be Class A involving cellulosic or other polymeric materials. Flammable liquid fires, which present problems involving their easy spread when attacked with water streams, are usually effectively controlled by use of foams as a barrier between the liquid fuel and surrounding oxidizer. It is assumed that fires of this type will not be the ones of major concern in hypobaric and hyperbaric chamber operation. Electrical equipment fires are usually assumed to present a shock hazard when attacked with solid water streams. Foams can be effective on such fires. In the following discussion, it is assumed that the chambers involved will probably have electric power circuitry, which can be de-energized if a general attack is to be made on a potentially large fire.

Magnesium or other flammable metal fires require special consideration (31). Review papers on ignition hazards of metals in both air and oxygen enriched atmospheres include those by Kimzey (32), Laurendeau (33), and White (34).

The extent to which each of the previously mentioned extinguishing actions are considered applicable to the closed system representing a space, land-based, or undersea cabin or compartment will be reviewed after a brief discussion of some characteristics of the extinguishment problem.

In addition to the difficulties imposed by burning characteristics of materials under high oxygen concentration, fire extinguishment in spacecraft must recognize the probability of zero gravity conditions, the difficulty of removal of toxic fire gases, and the limited ability of removing persons from the fire environment. Other earth based closed systems face quite similar problems, with the exception of that of zero gravity, which may make them even more hazardous with respect to fire.

Both automatic and manual suppression system activation methods have advantages and disadvantages, and a combination is probably desirable for effectively preparing for a fire hazard. An automatic extinguishing system has the advantage of fast action without the need for crew decisions. On the other hand, a false alarm could bring unnecessary water or other extinguishing agents into the compartment with possible damage to instrumentation systems as well as shutdown of normal work activities. Such action would be unacceptable. Manual systems permit hazard assessment by crew members and localized application of extinguishing agents, and thus avoid waste of available extinguishing material and limit portions of the chamber which might be affected. On the other hand, in oxygen enriched atmospheres, fires may run out of control in a matter of seconds; and total reliance on manual fire suppression methods could delay action beyond safe limits.

Explosion suppression techniques involving explosive-like dispersal of inhibitors considered by Roth (5) are appropriate in the presence of volatile flammable liquid fuel spills or flammable gases. They have been used to provide good protection in small spaces such as aircraft fuel tanks, and may limit peak pressure to levels safe for the equipment and space involved. The complexity of control equipment involved for large volumes and odd compartment or tank shapes, as well as the additional ignition hazards introduced by the complex wiring required for system installation, must be recognized if such systems are to be used. Further, quick application of the fire suppression agent may involve blast effects, most distressing and possibly dangerous to human survival (35).

Evacuation methods are considered by Roth (5) to be "effective in space-vehicle compartments with oxygen atmospheres." However, as noted by Roth, evacuation requires the donning of a space suit which can be a time-consuming process. Evacuation is not considered feasible where the avoidance of a very rapid and serious fire is the primary objective.

Ciccotti, in 1960 (4), listed criteria for selecting a fire extinguishing agent. These included: effectiveness on all classes of fires, applicability in the space environment, and low toxicity. He noted that there was not an agent known at that time that met all the requirements. The same comment has been repeated many times. Work and methods developed for achieving performance he and others have proposed will be reviewed.

3.1 Extinguishment through Cooling

Water is the common cooling agent for fire fighting. Its high latent and specific heats make it unusually effective. Its nontoxic nature and ease of reuse, if collected in a sump, make it an ideal agent for many fires. In a closed system, especially involving oxygen enrichment, prompt application of water to incipient fires is vital. Not only can fires in oxygen enriched atmospheres grow very rapidly, but the application of water spray to a well-advanced fire can result in flash steam generation with dangerous over-pressures. Under such conditions, it is extremely important to achieve rapid detection of the fire and actuation of the spray system.

Systems of this type have been studied by Eggleston (36) (37) (38) and (39), Goonan (40), Kimzey (35), and Denison (41) and (42). Eggleston reports that either ultraviolet or infrared detectors, when combined with a combustion product detector, provide a basis for fast detection and spray system actuation. He further reports that because combustion product detectors are sensitive to atmospheric density changes, they require special engineering design consideration for fully satisfactory operation. He suggested that, when detection is provided by the combustion product device alone, there would be merit in override of automatic extinguishant application and use of a hand-held hose on the smoldering fire (37).

Because of the need for good penetration in high pressure chambers, Eggleston considers the use of nozzles of 30, 60, and 90 degree spray angles preferable to nozzles of larger angles. His studies indicate that with increasing chamber pressure the developed spray angle is reduced when the 30, 60, and 90 degree nozzles are used. For the larger spray-angle nozzles, the developed spray angle increases with increased chamber pressure. The nozzle pressure of 30 psig Eggleston used is lower than that recommended by Kimzey (35); Kimzey's recommendation probably is significantly dependent on nozzle design and thus is probably not uniquely appropriate.

Eggleston recommends nozzles that are provided with large fluid flow passages as well as internal rather than external baffles to create jet breakup. Sprays of rather coarse droplet size are preferred to permit adequate penetration or throw onto the burning material. Rasbash (43) in his excellent review of fire extinguishment by water sprays draws attention to the importance of placing the water on the fuel bed. He emphasizes the fact that fires can be much more efficiently extinguished by cooling the fuel than by cooling the flaming gases. This consideration, of course, assumes that flash generation of steam is not being considered as a means for inerting the atmosphere surrounding a fire. Rasbash points out that the throw of the spray is increased much more easily by increase of water flow or decrease in spray angle rather than by an increase in pressure.

Because of the importance of ambient atmospheric pressure on spray development and penetration or throw, an attempt was made to find reports of systematic studies on this effect. In studies with swirl type turbine combustor nozzles of various designs, DeCorso (44) shows that fuel spray cone angle ratio is a function of the product of nozzle pressure drop and the 1.6 power of the gas density for vessel absolute pressures varying from 1.5 to 114 psia. Figure 6 illustrates the type of correlation achieved. While his work was done with fuel oil sprays, similar effects would be expected for water. Fraser (45) emphasizes the importance of chamber pressure on spray development and presents some data on the effect of air density in the hypobaric range on spray particle diameter and dispersion. He reports that mean drop size and dispersion are always greater at low ambient density. Ault (46) reports results of a few laboratory tests on the influence of ambient pressure and nozzle pressure drop on spray discharge pattern and flow rate. The ambient pressures used varied from one to six atmospheres. Although Eggleston (37) made a fairly detailed empirical study of this effect, it would seem to merit even further study. Kimzey (35) reports that overlap of sprays in his experiments was such that there was no coverage problem when operating the chamber at varying pressures.

Writers do not agree on the quantity of water required for fire extinguishment. This results from differences in assumptions made on the quantity of fuel, the nature of the fire to be controlled; the usual conservatism of the fire protection engineering personnel; and, probably, more importantly, the lack of definitive experimental data. Segal (48), on the basis of hyperbaric chamber tests, suggests water application at the rate of one gal/ft² min based on floor area. When this spray impinged directly on the fire, extinguishment was usually effected in less than 25 seconds. Denison (42) reported success in use of water at 5 ml/cm² min applied

to the involved surface for control of overalls fires in pure oxygen. This application rate, which corresponds to 1-1/4 gal/ft² min based on envelope area, is quoted by and apparently endorsed by NFPA (1). Ault (46) concludes that definitive tests on application rates have not yet been made. Kimzey (35) used one nozzle per 7 ft² of inside chamber wall area; extinguishment was achieved in times varying from 5 to 14 seconds with water flow rates per nozzle of about 0.7 gal/ft² min of chamber envelope area. Table III summarizes the application rate data derived from several references. Most of the writers (35) (37) (47) and (48) seem to recognize the importance of using horizontal and diagonally upward, as well as downward, application of sprays for fast water application to all parts of fire involved material.

Both Eggleston (37) and (38) and Kimzey (35) recognize the problems connected with proper nozzle functioning when compressed air is used as the driving force for water held under pressure in a reservoir and floated above the pressure of the compartment atmosphere. The dissolved air tends to flash to gaseous form disrupting flow through the discharge lines. Techniques for avoiding this problem, as well as means for preventing release of the propelling gas after the water supply has been exhausted, have apparently not been explored in much detail. The suggestion to use a pump rather than a stored pressure system has been made by both Goonan (40) and Kimzey (35), but a careful engineering study will be required on system dynamics to insure fast application before such a suggestion can be accepted. Eggleston's work (38) provides some assurance that a system of this type can achieve fast application and control action. Using low inertia submerged pumps and water charged sprinkler lines made possible by installing check valves in the supply piping, he was able to produce spray discharge within 2 seconds of system actuation. Eggleston (37) points out the obvious need to deactivate electrical systems in the chamber once extinguishment is initiated.

There seems to be a consensus that, for earth-based hypobaric and hyperbaric chambers, water spray systems have much to offer. The weight penalty involved is great, but this can be accepted for a land-based or underwater system. For the hypobaric space cabins, on the other hand, liquid water spray systems do not appear to be the best answer. Not only is weight a serious problem, but the cleanup in a zero gravity environment poses many difficulties. Capillarity and surface tension effects would still be operating, so towels would be useful. Perhaps the most practical means would involve opening a hatch to allow the release of water vapor into space. Heating would seem necessary to reduce ice formation and permit rapid cleanup. Since current practice apparently does not involve hermetic sealing of the electronic equipment used, the influence of moisture on flight instrumentation in the space cabin poses a further serious problem and a

convincing argument against any but localized application of water. On the other hand, there may well be circumstances where portions of space stations would benefit by protection available from a sprinkler-type system.

The suggestion has been made by Kimzey (35) that water sprays can be expected to reduce significantly the concentration of water soluble gaseous combustion products resulting from a fire, but the data he reports on gas concentration measurements after fire tests do not seem to support this suggestion. Perhaps this discrepancy results from the coarse water sprays and brief operating periods used.

Huggett (7) and (17) suggests that the heat capacity of the ambient atmosphere may, if sufficiently high, have a significant inhibiting effect on fire development, or even serve to quench a fire which has started. A recent report by McHale (49) explores the use of three fully fluorinated compounds (CF_4 , C_2F_6 and C_3F_8) as inerting and extinguishing agents. Studies of inerting effects, thermal decomposition products, and reactions of animals exposed to high concentrations of these fluorinated gases suggest that CF_4 has considerable merit as a nontoxic inerting agent. The studies were unfortunately limited to mixtures of air with the agent as a diluent or such mixtures with sufficient additional oxygen to maintain a 21 percent oxygen concentration. Figure 7 shows the approximate limits of effectiveness of some mixtures for which CF_4 appears useful in air at atmospheric pressure. However, Huggett privately reports that studies made in 60-40 mixtures of CF_4 - O_2 at atmospheric pressure have adequately inerted the atmosphere to prevent combustion of tissue paper. This aspect of cooling as an inhibiting process seems most interesting and deserves further consideration.

Another aspect of fire extinguishment through cooling, reported by Durfee (50), involves the use of a metallic heat sink adjacent to flammable materials. The technique has utility for reduction of material flammability, but the literature review has not found reports of application of this technique to materials such as fabrics, including clothing, where presumably the major hazard exists.

3.2 Extinguishment through Separation of Reactants

It seems obvious that if the two reactants in a fire can be isolated from each other the fire will cease to exist. How to accomplish such separation with the required speed, in a practical manner, in a closed chamber is far from clear. Either the fuel or the atmosphere must be removed. On initial consideration, the possibility of dumping the oxidizing atmosphere to the void in space, through the use

of a quick opening hatch, is an attractive one for control of a serious fire (5). As mentioned earlier, the need for fast action, the hazards of decompression on chamber occupants, together with the probability of thermal damage to vent opening seals have apparently militated against use of this technique in space. Provisions have been made for use of pressure release and a quick opening hatch while the space vehicle is on the ground (51). This type of venting does not achieve complete removal of oxygen and by itself would not provide an effective extinguishment capability.

In a closed system it will usually be difficult to remove and dispose of the fuel. A small amount of fuel can be covered with a metallic or other enclosure, and the fire can be controlled by isolating it from the ambient oxidizer. The use of foam as a blanket to cover an ignited material may provide another separating medium. Systems of this type have been considered for use in hypobaric space chambers. Charno (52) reports a series of tests in which he was able to use high expansion foam to extinguish fires involving foamed polyurethane and cotton smocks. He concluded that the foam system was practical, that no toxic combustion products were introduced by the use of foam, and that a system capable of 20 percent flooding of a 10,000 cu. ft. cabin would weigh about 50 pounds. In one test at 16.5 psia pure oxygen, a fire in a 2 x 12 x 12 inch slab of foamed polyurethane was extinguished within 4.65 seconds of activation of the system and 4 percent of the fuel was consumed. In another test at 9.8 psia pure oxygen, a laboratory coat was ignited and the foam system activated about 4 seconds after ignition, the fire was extinguished about 19 seconds after activation, and about 70 percent of the coat was consumed.

Both of these, as well as other tests performed, were conducted with the foam generator located within 3 feet of the flammable material. While a foam system may prove ideal when the location of a fire can be identified beforehand, the time required to form and move a foam bank to a fire seems to be prohibitive in the high oxygen concentrations expected in spacecraft. Nevertheless, such a system might prove of merit in a medical facility or in special, small area, high hazard locations where open sprays or chemical agents might be intolerable.

Charno (52) proposes further studies of foam systems to consider the special problem of zero gravity. Presumably, these studies would involve agglomeration of the foam into a cohesive bulk sufficient to produce effective results. This foam generation and application visualizes a relatively fixed installation with capability for rapid production of large volumes of foam. Perhaps provision could be made for ducting a portion of the foam generated by means of a fabric or other flexible hose to the fire site. A small first-aid foam generator,

developed to serve a similar need, is being supplied for possible use during an Apollo flight. The initial proposal for development of this device appears to have been made by Somerville (53) and a prototype device was later defined (54). A halon 122 ($\text{C Cl}_2 \text{ F}_2$) emulsion in water with added surfactants is placed in a small portable container designed to be used by one hand. The outlet nozzle is designed so that the generated foam can be laid down as a thick ribbon at the site of a fire, or alternatively the foam can be inserted through small openings of fire-affected equipment to occupy the internal voids. Proof tests of the device reported by Adams (55) suggest that it comes close to meeting the required capability of producing 2 cu. ft. foam after 18 days of shelf life. Reemulsification of the foam liquid is reportedly required after that time. Although this device appears to be an interesting development intended primarily for application on electronic-type fires, it also appears to be useful for other small localized fires. However, it would appear to be almost useless under large-scale, rapid fire development in a spacecraft cabin.

The use of inert gas as an extinguishing agent under zero gravity conditions seems to have some merit, although the manner in which it could be applied to displace oxygen from the vicinity of the fire would seem to require some study. Both Durfee (50) and Neustein (30) have reported effective extinguishment of exposed localized fires with inert gases.

3.3 Extinguishment by Dilution or Removal of Fuel

Dilution of a flammable gas, liquid, or even solid fuel by solution or admixture of an inert substance can serve as a means of extinguishment. The action of diluents is sometimes considered as a special case of extinguishment by cooling. It seems likely that, apart from consideration of the oxidizer concentration in the chamber atmosphere, such a technique will not be extensively used for fire extinguishment in hypobaric or hyperbaric chambers.

Although fuel removal seems unlikely to provide a useful fire extinguishment procedure in a chamber, it seems desirable to emphasize the merit of avoiding the presence of fuel in hypobaric and hyperbaric chambers. Thus, the elimination of potential fuels in compartments can greatly reduce the fire hazard and decrease the urgent need for active fire fighting equipment.

3.4 Extinguishment through Chemical Action

There are a number of extinguishing agents which are so dramatic in their ability to control and extinguish fire that it seems difficult to attribute their effectiveness to other than chemical processes. Such agents include the halogenated hydrocarbons and the dry chemical powders such as alkali metal carbonates and ammonium phosphates. The concentrations in which these agents are effective seem far too low to suggest that their effectiveness can be explained through physical processes (56) and (57). Some physical effects are undoubtedly active during use of these agents; for instance, radiation shielding properties are exhibited by dry powders when dispersed in air. However, the fact that other materials which exhibit similar physical characteristics are much less effective as extinguishing agents reinforces our conclusion that chemical processes are of major importance.

It is beyond practicality to discuss the various theories relating to the role played by chemical inhibiting agents. The survey papers by Friedman (58), Creitz (59), and Belles (60) may be referred to for this sort of detail. Suffice it to say that the halogenated hydrocarbons and light metal carbonates have proved especially effective as extinguishing agents.

Initial use of the halons, and especially CF_3Br , was directed towards application to the fire itself, as had been the custom with water, foams, and dry powder agents. The observation of Simmons and Wolfhard (61), later confirmed by the work of Creitz (62), drew attention to the very low concentrations at which CF_3Br when dispersed in air was capable of inerting the air and extinguishing a fire. These findings became increasingly important when it was established that for short periods and without undue toxic hazards, humans could tolerate ambient concentrations of CF_3Br , which would render the atmosphere incapable of supporting combustion. Furthermore, at these same concentration levels, CF_3Br was effective for extinguishing most fires which require air as an oxidizer. These findings, which were becoming available at the time of the Apollo fire, stimulated increased study of halogenated and other compounds as fire extinguishing agents. Numerous studies of possible application of CF_3Br have been made; some of these have further demonstrated the great effectiveness of the agent for fire suppression purposes. Martindill (63), Eggleston (31), Kimzey (64), and others performed tests on the effectiveness of CF_3Br on hyperbaric chamber fires. Eggleston concluded that such systems were practical and could be designed to operate very rapidly, but the blast effects from insertion of the agent into the chamber, the inevitable pressure rise, and the possible hazards from thermal decomposition products when applied to fires have hindered enthusiasm for recommending CF_3Br for use in human-occupied closed chambers.

The problem of decomposition products results from the fact that HF, HBr, CO, and the combustion products of the fuel involved can result when CF_3Br is applied to actively burning fires. The yield of these products is naturally dependent on the size of the fire and the promptness with which extinguishment can be achieved. Such products are, of course, most irritating, and in sufficient concentration can prove lethal. Also, when combined with the moisture presumably present in an atmosphere occupied by humans, these decomposition products will become serious corrosive agents likely to damage electronic and other instrumentation components. Because of this potential hazard, most recent studies relating to possible use of these agents have included measurement of decomposition products. These include a paper by Ford (65) on the suppression of computer fires and a related paper by Kimzey (64). Regardless of the hazard to equipment, it seems evident that occupants of chambers in which fire extinguishment has been achieved by a halogenated gas would be most uncomfortable until the atmosphere they were breathing had been cleared of the resulting decomposition products. It is not known if consideration has been given to the influence of pyrolysis products and extinguishing agents on the air conditioning equipment used to maintain the chamber atmosphere, but studies have been performed on equipment used in submarines. Presumably the information available may be applied to hypobaric and hyperbaric chambers. Although CF_3Br has proved itself very effective as a fire extinguishing agent, the inconveniences and possible hazards imposed by its use in occupied spaces have delayed, if not prevented, its acceptance. However, when its application is controlled by a reliable and fast-acting fire detection device, it could fulfill a real need in unoccupied spaces. On the other hand, the question may well be raised as to why a fire supporting atmosphere should be used in such spaces at all.

A further, but probably minor, problem relating to the use of CF_3Br for fire extinguishment involves the fact that its vapor pressure is so high at normal temperatures that it is usually stored in liquid form at a pressure of about 214 psia and 70°F. Its application thus involves expansion to a gas, with the resulting refrigeration effect associated with its latent heat of vaporization and required superheat. The temperature change of an air atmosphere at 70°F diluted with 7 percent of CF_3Br evaporated from liquid at 70°F would be about -47°F without consideration of heat transfer from the fire, occupants, or the chamber structure. This may or may not be a problem depending on other conditions, but it is a fact that should be recognized.

One outstanding advantage of a gaseous extinguishing agent is that cleanup can readily be achieved by simply venting the compartment. This assumes, of course, that corrosive or other damage to the system will not occur as a result of agent use.

There are many chemicals which have been identified as having merit as extinguishing agents when propelled as a cloud, in powder form, to envelope a fire (56) (57) and (58). The sodium and potassium bicarbonates, ammonium phosphates, and others have found practical use. The carbonates are effective on Class B and C fires, but are not usually considered appropriate for fires in cellulosic (Class A) materials. Some of the ammonium phosphates have proved effective on all three types of fires (66). There appear to be few studies of the use of dry chemicals on fires supported by oxygen enriched atmospheres under hypobaric or hyperbaric conditions.

The limited study of the effectiveness of these compounds under the conditions of interest here may have resulted from their low effectiveness on fires involving cellulosic and similar type fuels. The problem imposed by the need for cleanup after use of dry chemicals is also a significant one, especially in a space vehicle. In earth-based chambers, this type of problem does not appear to be of decisive consequence. Probably the real reason for lack of enthusiasm for dry chemicals results from the superior properties of water. The penetrating effect of water both through direct flow and capillarity through fabrics, as well as the cooling effect, is not matched by the powders. Effectiveness of dry powders on fire in an oxygen enriched atmosphere appears to require further study before confidence can be placed in their use.

4. Engineering Considerations

The design, construction, and safe operation of chambers for use under hypobaric or hyperbaric conditions require a high level of engineering competence. It is quite beyond the scope of this report to enumerate the various problems which must be recognized. A few points should be made, however, with regard to certain fire hazards.

4.1 Pressure Rise Resulting from Fire

As all internal combustion engineers are aware, fuel burned in an enclosure, whether in premixed form as in a gasoline engine or even in the form of pulverized coal in some diesel engines, may burn releasing heat with resulting high temperatures and pressures. In a similar way, an uncontrolled fire in a closed chamber will burn until either fuel or oxidizer is depleted. The temperatures and pressures reached will be dependent on the rate of combustion, the ability of the chamber to absorb the heat

generated, and the quantity of oxygen or fuel, whichever is limiting with respect to the chamber volume. The Apollo cabin fire resulted in rupture of the cabin enclosure at an estimated pressure of about 29 psia, almost twice the operating pressure normally used in the chamber. The fire had burned for about 20 seconds prior to rupture. Quite apart from the structural failures, such rapid pressure changes obviously pose a severe hazard for any human occupants.

Botteri (9) has performed some experiments on fires in enclosed chambers, and Atallah and de Ris (67) have developed a theoretical model for prediction of pressure and temperature rise in closed systems. This model assumes an initial small fire with a subsequent exponential rise in burning rate. Adiabatic and noncondensing conditions have been assumed for the combustion products. The pressure time development rate they predict is in close agreement with Botteri's findings as well as the data available from the Apollo fire (68).

4.2 General Safety Consideration

The increasing use of hypobaric and hyperbaric chambers has stimulated recognition of the hazards involved, and resulted in the publication of NFPA standards on hyperbaric facilities (2) and hypobaric facilities (3). Each standard presents a discussion on the nature of the hazards and proposes construction, equipment, administration, and maintenance details appropriate for safe use of facilities. Recommendations are also included on the appropriate response by both chamber occupants and outside attendants in the event of a fire.

Linderoth (69) describes safety features and operating procedures which have been found desirable as a result of 10 years experience with the hypobaric and hyperbaric chambers at Duke Medical Center. He emphasizes the fire hazards posed by electrical equipment within the chamber and recommends isolation transformers to reduce the hazard if one side of the electrical circuit becomes grounded. Suggestions are made for the use of air-driven rather than electrical motors for rotating equipment. Multiple water spray hoses are recommended for first aid firefighting. Many other interesting techniques and features are proposed for safe operation of these chambers, and special emphasis is placed on the development and use of checklists in connection with the operation and maintenance of such chambers.

5. Recommendations

In the process of developing this review paper a large body of literature relating to fire extinguishment in oxygen enriched atmospheres was identified. The necessity for systematic consideration of various aspects of the subject resulted in identification of a number of technical areas where adequate data seems lacking; and, as a result, further research or developmental work seems appropriate. It should be observed, however, that the priorities assigned to work on these or other elements will be greatly influenced by other program needs and the degree to which general solution to technical problems is desired. In many technical fields an empirical approach to solution of a particular technical problem involving many variables is often the most expeditious solution, even if it may lack the technical finesse so prized by the scientist. As a result the following list of areas, which seem to warrant further work, is presented in the same order as their need is developed in the text.

1. The question of the amount of water and its appropriate application rate for prompt and efficient control of fires warrants further study. In hypobaric and hyperbaric chambers, the water application rates being recommended do not seem to be based on the chamber operating conditions, but rather on the prompt application of more than enough water to control the fire in the worst situation. Further work seems justified on the application rates as well as total quantity of water required as a function of chamber operating conditions and nature of the fire-fuel array.
2. The apparent absence of any consideration of use of thixotropic materials to secure greater adhesion between applied water and the fuel and/or surface active additives to increase wetting and penetration characteristics seems surprising. To permit more efficient use of water, work on these materials has been done by both the Navy and the Forest Service. Work in this area might lead to effective extinguishment with much smaller quantity of water application. At least, consideration should be directed toward possible advantages which might be achieved through use of water additives to modify extinguishment performance of water.
3. The problem of nozzle design and spray behavior in hypobaric and hyperbaric chambers appears to be largely based on empiricism. It would seem profitable to conduct some systematic studies, perhaps similar to those of Fraser (45) and DeCorso (44), through which data could be accumulated to assist in the selection of spray systems with predictable performance characteristics.

4. The water spray suppression systems which have been reported in the literature involve the concept of fast application of water to all portions of the chamber. It would appear useful to explore the feasibility of defining fire zones within the compartment which would be monitored by different sensors, and thus form the basis of control of localized fires without the indiscriminate spraying of the whole chamber. A technique of this type would appear useful when expensive and complex equipment might be required in the chamber which could be easily damaged by water. In other situations, the indiscriminate use of water application may not be objectionable.

5. The recent findings of Huggett (17) and McHale (49) on the effectiveness of the fully fluorinated compounds, and especially CF_4 , for inerting an oxygen atmosphere to combustion reactions seem most interesting. It appears likely that further verification of the reported tolerance of animals to high concentrations of CF_4 could pave the way for experiments with humans and eventually validate the usefulness of this gas as a safe inerting agent.

6. In some circumstances, and especially medical facilities, the use of water sprays might prove most hazardous for a human patient. It may be desirable, therefore, to explore the feasibility of using foam as an efficient extinguishing agent that is accompanied with much less potential hazard to the patient. These studies would, of course, involve consideration of biologically aseptic foam compounds.

7. The behavior of fires under low or zero gravity fields is still a subject of considerable uncertainty. There are many related experiments which could be performed in the proposed orbiting laboratory. Some of these would involve study of small combustion systems, while others might be devoid of actual flames but involve study of convection and diffusion phenomena related to gas flow of combustion products or application of an inert gas cloud as an extinguishing medium.

8. There is, of course, the continuing need for development of materials which will serve as replacements for their more flammable or combustible commonplace counterparts. NASA and others have made real progress in this direction. Further work in this area would do much to alleviate the problem of unwanted fires.

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Table for Conversion to SI Units

The units used in this paper are those derived directly from the references involved. The following table provides factors by which the unit given must be multiplied to yield the appropriate SI unit.

Physical Quantity	to convert from	to	multiply by
Length	inch, in.	meter, m	0.0254
	foot, ft.	meter, m	0.3035
Area	square foot, ft ²	square meter, m ²	0.09290
Volume	gallons, g	cubic meter, m ³	0.00379
	cubic foot, ft ³	cubic meter, m ³	0.02832
	cubic centimeters, cc	cubic meter, m ³	0.00010
Velocity	inches per second, in/sec	meters per second, m/s	0.02540
	centimeters per second, cm/sec	meters per second, m/s	0.01000
Volume per unit area	gallons/ft ² , gal/ft ²	meter ³ /meter ² , m ³ /m ²	0.04080
	milliliters/cm ² , ml/cm ²	meter ³ /meter ² , m ³ /m ²	0.01000
Pressure	millimeter mercury, mmHg	Newtons per square meter, N/m ²	133.3
	psig, psia, lb/in ²	Newtons per square meter, N/m ²	6895
Force	pound, lb	Newton, N	4.448
Temperature difference Temperature	Fahrenheit, °F	Celsius, °C	1.8
	Fahrenheit, °F	Kelvin, °K	*

*since °F is not proportional to °K, the following formula is appropriate: $t_K = (t_F + 459.67)/1.8$

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ACCIDENT	SUSPECTED IGNITION SOURCE		SUSPECTED PRIMARY FUEL	SECONDARY FUEL	SUPPRESSION EQUIPMENT	EXTINGUISHMENT EFFORTS	TIME TO FATAL ENVIRONMENT (SEC)	PRIMARY CAUSE OF DEATH
	INSTALLATION	ENERGY						
<u>HYPOBARIC</u>								
9 SEPT. 1962 USAF	PERMANENT	ELECTRICAL WIRING	ELECTRICAL INSULATION	?	?	?	NOT FATAL	NOT FATAL
17 NOV. 1962 USN	PERMANENT	ELECTRICAL WIRING TO LAMP	ELECTRICAL INSULATION	COTTON TOWEL	ASBESTOS BLANKET	TRIED TO SMOOTHER WITH TOWEL-THEN BLANKET	NOT FATAL	NOT FATAL
27 Jan. 1967 APOLLO	PERMANENT	ELECTRICAL WIRING	ELECTRICAL INSULATION	CELLULOSE AND VARIOUS PLASTICS	NONE	NONE MENTIONED	< 14.7	ASPHYXIA
30 JAN. 1967 USAF	TEMPORARY	ELECTRICAL WIRING	COTTON CLOTHING	VARIOUS PLASTICS	NONE	NONE MENTIONED	< 90	HEAT
<u>HYPERBARIC</u>								
22 MAR. 1945 USN	?	ELECTRICAL	ELECTRICAL INSULATION	WOOD GRATINGS	?	?		?
1953 G8	WRONG LAMP	ELECTRICAL LAMP	CANVAS	CELLULOSE	NONE	STOMPED ON FLAMES	< 60	SHOCK
16 FEB. 1965 USN	TEMPORARY	ELECTRICAL SCRUBBER	INSULATION FILTER MATERIAL OR HYDROCARBON	CELLULOSE RUBBER	BUCKET OF H ₂ O	NONE MENTIONED	< 15	TOXIC PRODUCTS, HEAT AND PRESSURE
9 OCT. 1967 JAPAN	TEMPORARY	CATALYTIC HEATER	?	?	?	?		?
4 APRIL 1969 JAPAN	TEMPORARY	ELECTRICAL CORD	ELECTRICAL INSULATION	CELLULOSE AND PLASTICS	NONE	STOMPED ON FLAMES		SUFFOCATION
1969 US	TEMPORARY	ELECTRICAL LAMP	COTTON SHIRT	CELLULOSE AND RUBBER	BUCKET OF H ₂ O	NONE MENTIONED	FEW	PRESUMABLY HEAT
8 FEB. 1970 JAPAN	REGULAR	ELECTRICAL HEAT LAMP	MATTRESS	BEDDING	NONE	NONE MENTIONED		

TABLE I. Abridged summary of hypobaric and hyperbaric chamber fires.
Reproduced from Alger and Nichols (12).

Overalls and Condition	Ambient P _{O2} (mmHg) at which:			
	Ignition occurs and: (t _{ign} - 2 sec) is		Ignition and 50% skin burn is likely and: (t _{50 D} - 2 sec) is	
	< 5 sec	< 20 sec	< 5 sec	< 20 sec
"var damp, new" in pure O ₂	320	160	520	300
"dry new" " " O ₂	150	100	470	230
"old damp" " " "	100	75	150	75
"wet new" " " "	> 750	> 750	> 750	> 750
"dry new" O ₂ /N ₂ at 750 mmHg	320	160	500	400
"dry new" O ₂ /He at 750 mmHg	500	280	650	450
"dry new" in O ₂ /N ₂ at > 350 mmHg (P _{N2} < 50 mmHg)	150	100	> 300	> 300
"dry new" in O ₂ /He at > 350 mmHg (P _{He} < 50 mmHg)	200	100	> 300	300

The table has been constructed on the assumptions that:

- the normal range of manual response times to unexpected emergencies is 5 to 20 sec.
- a hypothetical extinguisher system exists that takes 2 sec to come into full operation.
- no automatic fire sensors are present.
- the ignition wire of the present experiments took 2 sec to reach red heat.

Table II. Circumstances in which manual responses would be unable to prevent ignition of clothing or ignition of clothing and 50% destruction of skin. Reproduced and adapted from Denison et al (22).

Worker & Reference	Segal (48)	Kimzey (35)	Eggleston (37)	Eggleston (38)	Denison (23)
Chamber Dimensions Ft	10 Diax20	5 Diax10	7½ Diax13½	7½ Diax13½	Unknown
Floor Area (Est) Ft ²	160	33	50	50	Unknown
Chamber Envelope Area Ft ²	786	230	318	318	651
Number of Nozzles	20	30	Varied	18	5
Discharge Rate GPM/Nozzle	8	5.7	Varied	10.7*	16
Water Application Rate GPM/Unit Envelope Area	.20	.74	.31	.61	1.23
Water Application Rate GPM/Unit Floor Area	1.0	5.15	2**	3.9	Unknown

* Since various types of nozzles were used this is only an average

** Application rate recommended by Eggleston (37)

TABLE III. Chamber dimensions and water application rates used in hyperbaric chambers. Data from various sources.

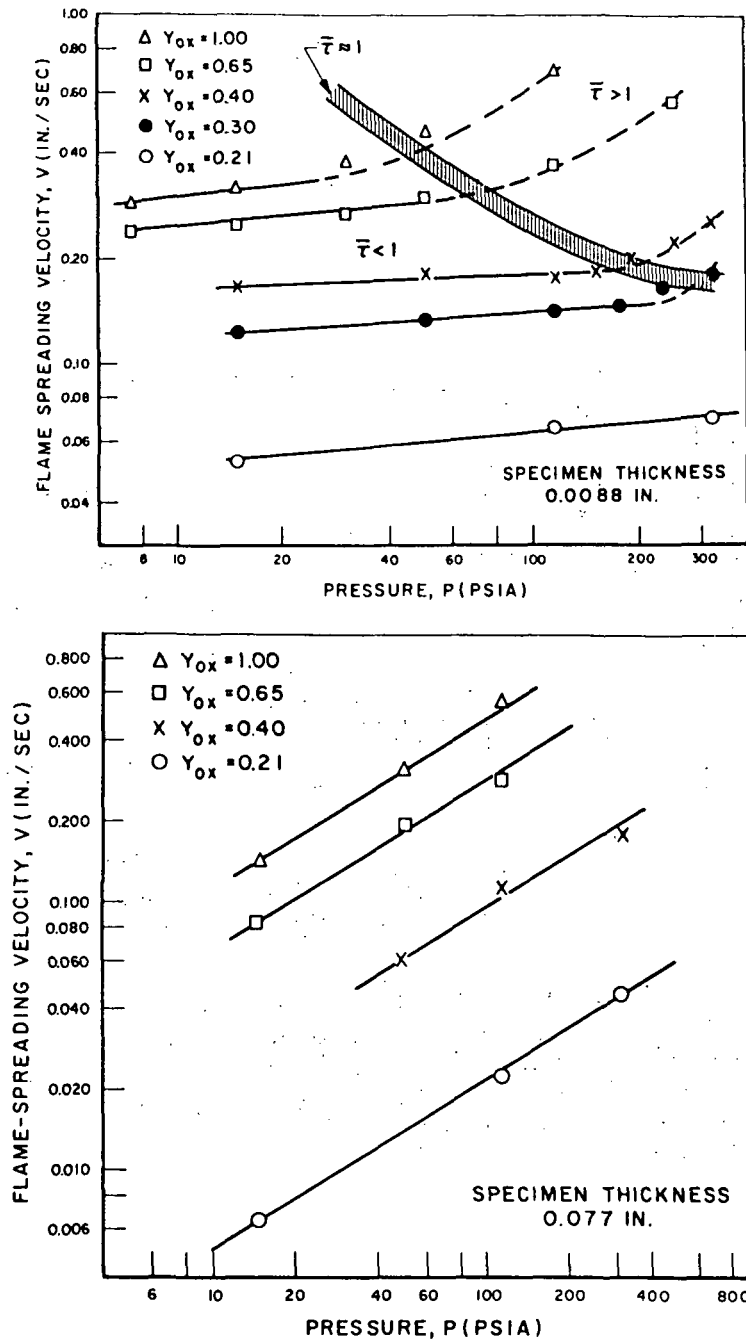


Fig. 1 Downward burning of cellulosic sheets at various O_2 - N_2 concentrations and pressures. Data from Lastrina, Magee, and McAlevy (14); Y_{Ox} is the mole fraction of oxygen in the combustion atmosphere. Note that the transition from thin to thick fuel burning rate occurs for $\bar{\tau} = 1$. This property is a function of thermal conductivity, density, specific heat, ignition region thickness and flame spread velocity of the solid material.

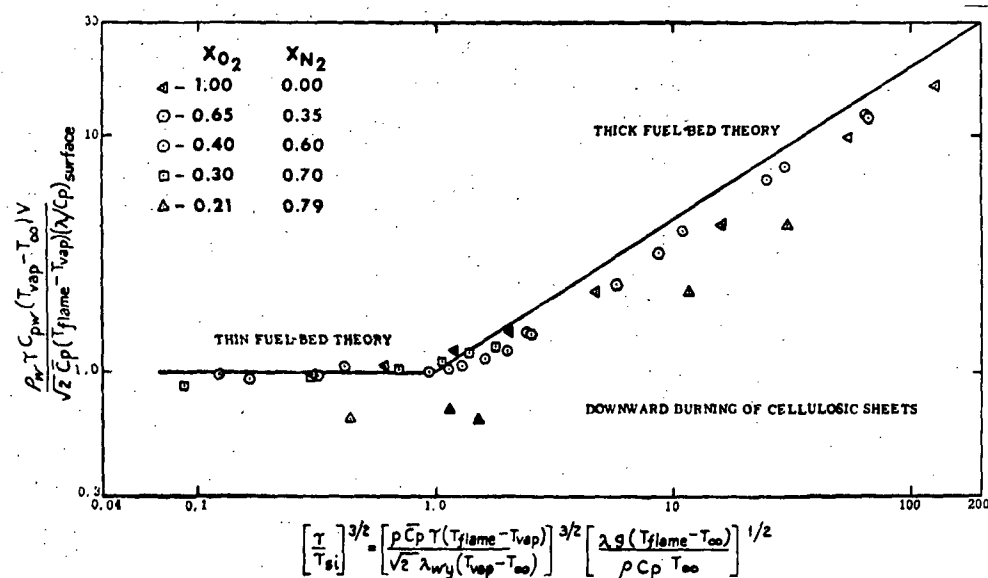


Fig. 2 Correlation by De Ris of data shown in figure 1. The ordinate is proportional to flame spread rate and the abscissa to pressure. Reproduced from De Ris discussion of reference (15). X_{O_2} and X_{N_2} are the mole fractions of oxygen and nitrogen respectively in the combustion atmosphere.

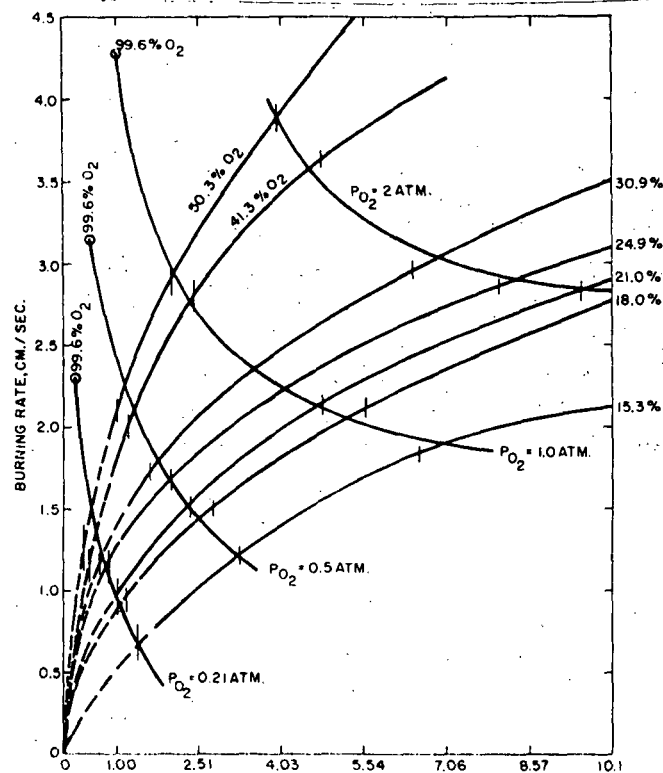


Fig. 3 Flame spread rate of filter paper strips, when burned at an angle of 45° with the vertical, as a function of ambient pressure and a range of oxygen concentrations. Reproduced from Dorr reference (11).

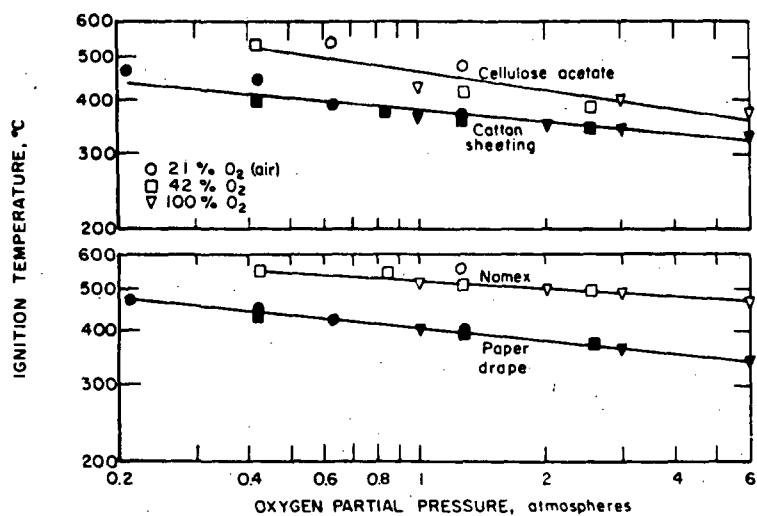


Fig. 4 Hot plate ignition temperature for polyethylene as a function of ambient pure oxygen pressure. Reproduced from Kuchta et al reference (18).

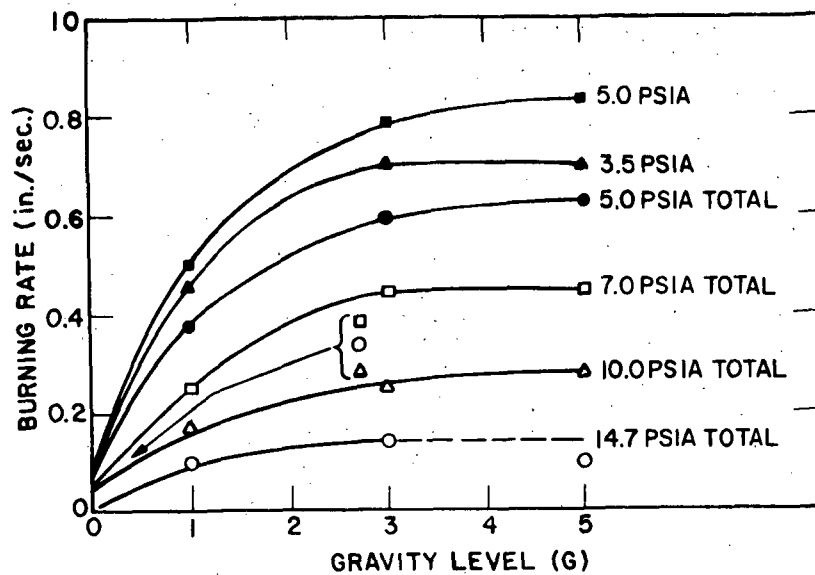


Fig. 5 Cotton cloth burning rate as a function of applied acceleration. The upper two curves are for pure oxygen. The lower four curves apply to nitrogen-oxygen mixtures with a constant oxygen partial pressure of 3.5 psia. Reproduced from Neustein (30).

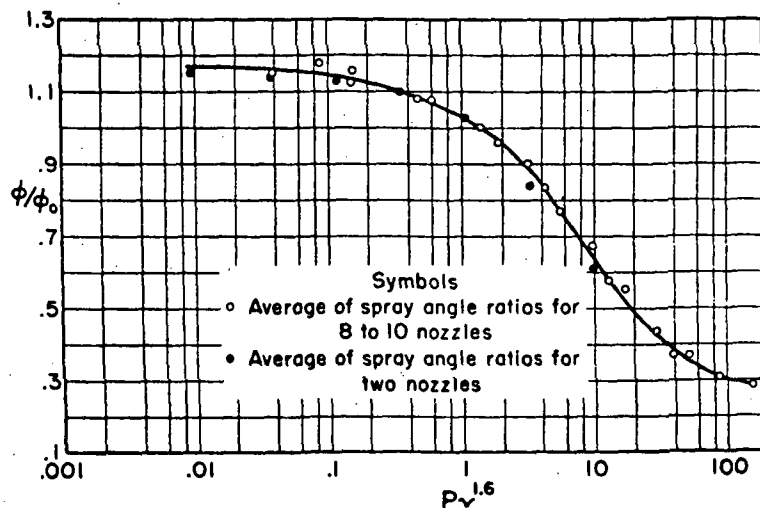


Fig. 6 Spray angle ratio, ϕ/ϕ_0 based on angle at atmospheric pressure, as a function of nozzle pressure drop P (lb/in²) times the 1.6 power of the gas density γ (lb/ft³). Data are for nozzles with spray angles less than 90°. Reproduced from De Corso reference (44).

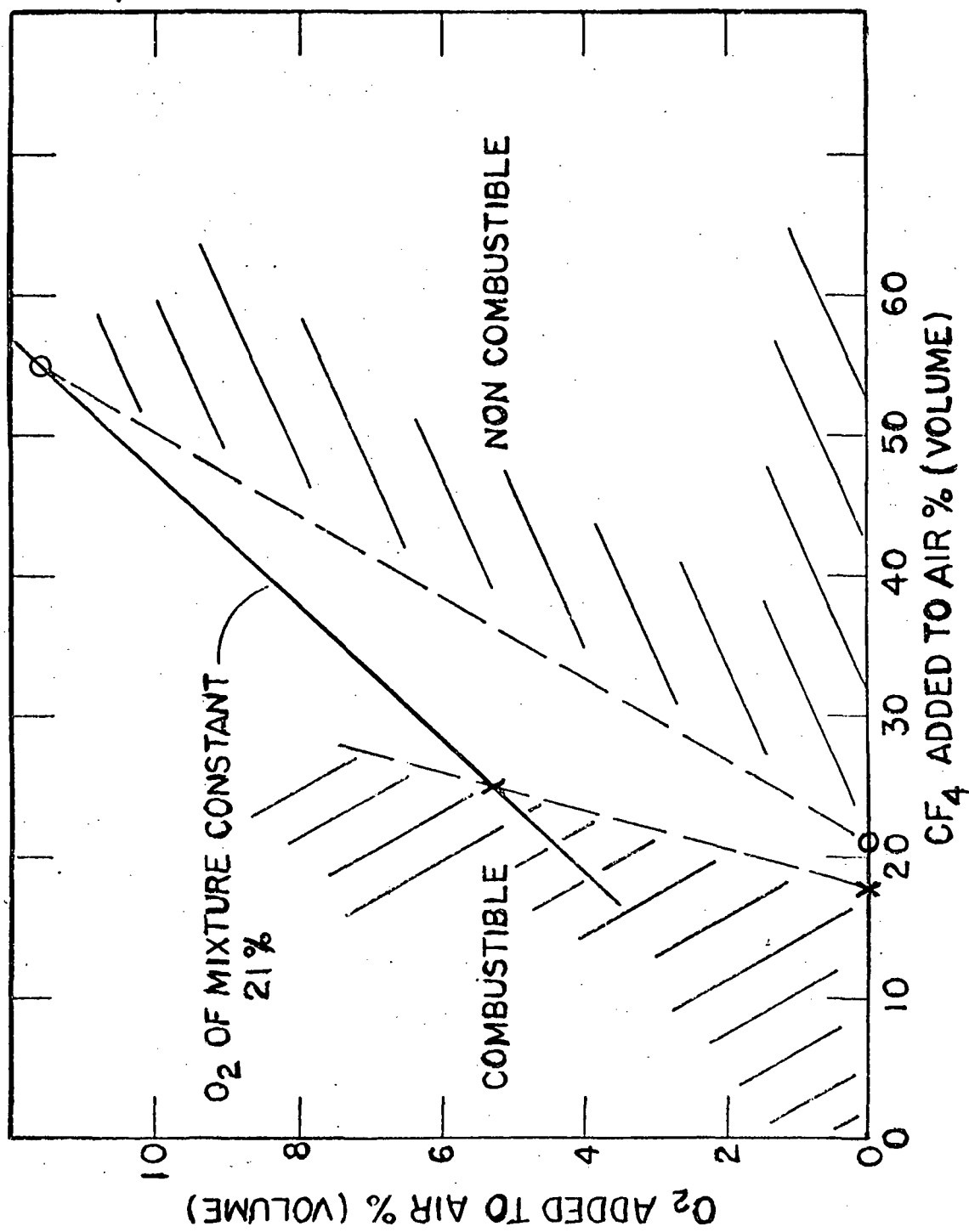


Fig. 7 Approximate boundary between gas mixtures which will and will not support burning of tissue paper at atmospheric pressure. Reproduced from McHale (49).